Phosphorus Loading from Urban Stormwater Runoff as a Factor in Lake Eutrophication: I. Theoretical Considerations and Qualitative Aspects[1]

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ABSTRACT

A theoretical fractionation of urban runoff phosphorus (P) according to its chemical mobility and potential biological impact is presented and the P fractions feasible for routine analysis established. Urban runoff P from two separate storm sewer systems draining residential areas in the Lake Wingra basin (Madison, Wis.) was characterized in detail. Flow-weighted mean concentrations of dissolved inorganic P (P_i) for individual runoff events ranged from 0.10 to 2.11 mg P/liter and generally comprized $\geq 79\%$ of the total dissolved P (P_t), allowing optimization of routine P characterization by the determination of dissolved P_i (or dissolved P_t) and total P. Flow-weighted mean concentrations of total particulate P (P_t) ranged from 0.14 to 2.37 mg P/liter. However, while the composition of the particulate P_t at the lower concentrations was widely variable, at the higher concentrations particulate P_t was constituted mainly of organic P (P_o). Flow-weighted mean concentrations of dissolved P_i were more consistently correlated at a significant level with particulate P_t and particulate P_o than with particulate P_i. The higher concentrations of dissolved and particulate P were associated with leaf and elm fruit fall, in the fall and spring, respectively, and with longer dry periods immediately before runoff events. A significant proportion (35 to 50%) of the particulate P_t occurring during the first flush and high flow phases of runoff events would remain suspended in the lake photic zone for several days. The upper limit for potentially available P in urban runoff can be given by dissolved P_i (or dissolved P_t) plus $0.25 \times$ particulate P_t, for the watersheds studied.

Additional Index Words: orthophosphate, particulate P, particulate organic P, particulate inorganic P, flow-weighted means, hydrographic stages, settling rates, sampling optimization.

Eutrophication or overfertilization of the surface waters of lakes along with the resultant excessive growth of nuisance algae and aquatic weeds remains one of the major environmental concerns. Phosphorus (P) has been projected as the major essential nutrient element most generally accessible as the target nutrient for the control of the offending plant growth (12, 13).

Phosphorus concentrations in urban runoff have attained levels as high as 4.93 mg P/liter, as soluble orthophosphate (3), with a range of 0.01 to ~1 mg P/liter being more common (1, 3, 11, 15, 26). Total P (P_t) concentrations from this source often range from 0.01 to 2.50 mg P/liter (1, 4, 11, 15, 17, 26). Although values as high as 43 mg P/liter have been reported (7). Flow-weighted averages of 0.076 mg P/liter, as soluble P (26), and 0.19 (1) and 0.208 mg P/liter (26), as total P, have also been measured. These values exceed greatly the critical threshold level of 0.01 mg P/liter of soluble inorganic P (P_i) originally cited by Sawyer (21) for algal nuisance conditions in lakes. Thus the eutrophication potential of urban runoff is undeniable.

In early studies of urban runoff quality, nutrient elements such as N and P were not determined (31). Subsequently, total P, acid hydrolyzable P, and soluble P (26, 29, 30) were the classes of P determined. More recently, orthophosphate (15) or operationally, dissolved reactive P (11), and total P have been measured in urban runoff. The selected analyses reflect the central interests of the particular investigations. Thus analyses that estimated dissolved P_i emphasized potential eutrophication effects.

However, a rational assessment of the contribution of urban runoff P to lake eutrophication requires that the importance of the different forms of P and their pattern of occurrence be understood. The current investigation was initiated in order to: i) examine the theoretical significance of various P species in urban runoff to lake eutrophication; ii) measure the concentrations of various P species in urban runoff; and iii) suggest target P species that would optimize both for analytical convenience and for the estimation of the eutrophication potential of urban runoff.

MATERIALS AND METHODS

Analytical Methods

All P determinations were made by the single reagent method of Murphy and Riley (14) using ascorbic acid as a reductant for molybdophosphoric acid. For dissolved P_i the reagent was added directly to the filtered (0.45-μm pore-size) untreated sample, while for total dissolved and total P analyses the reagent was added after the autoclave digestion of filtered and unfiltered samples, respectively, according to the persulfate oxidation method (28). Particulate P is given by the equation: particulate P = (total P) − (total dissolved P). Particulate P_i was determined from the amount of particulate P released as dissolved P_i by a 17-hour extraction with $1N$ HCl. Absorbance was measured at 712 nm on a Unicam SP1800 Spectrophotometer.

Sampling and Sample Handling

This investigation was conducted in Madison, Wisconsin, and utilized two storm sewer systems, Manitou Way and Nakoma (named after the major streets near the outlets) which drained areas of 56 and 615 ha, respectively. These were both established residential areas, with Nakoma having a small admixture of light commercial activity. Both areas were quite hilly, with 22% (Nakoma) and 26% (Manitou Way) being covered with impervious surfaces. Runoff from about 67% of the area draining into the Nakoma system empties first into a shallow holding pond (5 ha) which has a regulated spillway into the remainder of the storm sewer system.

These storm sewers, which emptied ultimately into Lake Wingra, were monitored intensively during storm and snowmelt runoff events occurring from fall 1971 through summer 1972. The Manitou Way sewer control is a concrete Palmer-Bowlus flume in the 15.24-cm-diam (0.5-foot) concrete storm sewer, and the Nakoma sewer control, a concrete V-shaped flume in the 183 by 122 cm (6 by 4 feet) box culvert storm sewer. Flow data was obtained as computer printouts of continuously recorded 5-min flow rates, courtesy of the USGS.

For most storms, especially in the earlier phase of the study, samples were taken manually every 2 to 5 min during peak flow and at larger intervals over the entire length of a storm. This was done by immersing polyethylene sample bottles (500 to 1,000 ml) 15 cm (6 inches) below the surface of the water in the appropriate flume. A Sigma-motor automatic sampler was installed in the summer of 1972 to facilitate representative sampling of runoff from long-duration storms. The sampler was not used for intensive investigations of relationships between runoff P concentrations and flow rates since a period of 8 min of continuous pumping was needed to obtain a sample volume of the desired magnitude; for many storms, flow rates changed radically within an 8-min period.

The runoff samples were analyzed as soon as possible after sampling (normally within a few hours) because of the well-known lability of P in aquatic samples. Samples were filtered (0.45-μm pore-size) and refrigerated at 4°C, if the time between sampling and analysis exceeded a few hours. Refrigeration time never exceeded 12 to 24 hours.

Determination of Settling Characteristics

Limited studies on the settling velocity of particulate P in runoff samples were undertaken. Three hundred ml of sample were agitated thoroughly in a 500-ml graduated cylinder at time zero. Aliquots were then removed from a 10-cm depth at different time intervals and analyzed for total P. The particulate P settling during appropriate periods was calculated from the difference between the determined levels of total P.

RESULTS AND DISCUSSION

Adequate assessment of the biological impact of urban runoff P in the photic zone of a lake, e.g., Lake Wingra, requires a fairly detailed characterization of the P present. Such a representation is given in Fig. 1. This fractionation scheme compartmentalizes runoff P according to the potential chemical mobility and biological availability of the various components.

For maximal biological impact, the runoff P must be in the photic zone of the lake and in a form directly available to plants. Dissolved P_i is directly available. In contrast, dissolved organic P (P_o) is available only indirectly and must be broken down to generate dissolved P_i. Particulate P that is sufficiently dense and large, e.g., sand and silt particles, to settle out rapidly from the photic zone likely has only a minimal impact on biological activity in lake surface waters. This P

Fig. 1—Fractionation of urban runoff P according to its potential biological impact on the lake photic zone.

would be involved only through interactions of the bottom sediment with the overlying water.

Suspended particulate P, depending on the duration of its stay in the photic zone and its chemical form, represents a potentially significant reservoir of P. Macroparticulates which remain in suspension are most likely to be organic materials, such as leaves, of low density. While most of the P in leaves is in the organic form and not easily available, it has been shown (5, 8) that dead leaves do contain a significant proportion of leachable P_i, especially after freezing. The portion of this leachable P_i which is not lost from the leaves prior to entry of the runoff into the lake will most probably contribute subsequently to the level of dissolved P_i in the lake surface waters.

Suspended microparticulates cover a wide range of possibilities—from phyllosilicate clays to organic materials. Suspended microparticulate P_o is probably only slowly available and then only through reactions mediated by microbes. The availability of microparticulate P_i is dependent on chemical rather than on biochemical reactions. This P fraction has been subdivided in a manner derived from that applied initially to soils (2) and extended to sediments (23, 33). The "available" P is equivalent to the NH_4Cl-P and the nonoccluded P. Various estimations of the sediment P available to algae using resins (6, 9) dilute acid or dilute base (6, 19) as extractants remove P primarily from the "available" P fraction described here. Where these microparticulates do remain suspended for an extended period, this P fraction may present algae with a substantial reservoir of P (6, 9, 19), especially during periods of rapid growth coinciding with depleted levels of dissolved P_i, e.g., midsummer.

While the above discussion provides some insight into the detailed theoretical composition of runoff P, such a complex scheme is obviously impracticable for routine analysis of runoff samples. Instead, it is more feasible to perform some simple gross analyses that would still allow approximation of the biological impact of runoff P in the lake photic zone.

Characterization of dissolved P in urban runoff to Lake Wingra is given in Table 1. Values are provided for both the Nakoma and Manitou Way storm sewers for dissolved P_i and total dissolved P (P_t). The samples were taken over a wide range of flow rates, P concentrations, and hydrograph stages, representing all times of the year. Nearest antecedent events occurred from a few hours to 12 days before the events sampled.

In general, the highest dissolved P_t levels were obtained in fall and spring runoff, coinciding with leaf fall and elm fruit fall, respectively. To a lesser extent, the time elapsed since the nearest runoff event contributed positively to the observed P concentrations. However, despite the range of conditions represented by the samples, the dissolved P_i constituted in all instances at least 79 and often >90% of the dissolved P_t. This finding indicates that almost all of the dissolved P in this runoff can be directly available for algal uptake if other conditions such as light and temperature permit, and it allows the P in solution to be characterized effectively by a single analytical measurement.

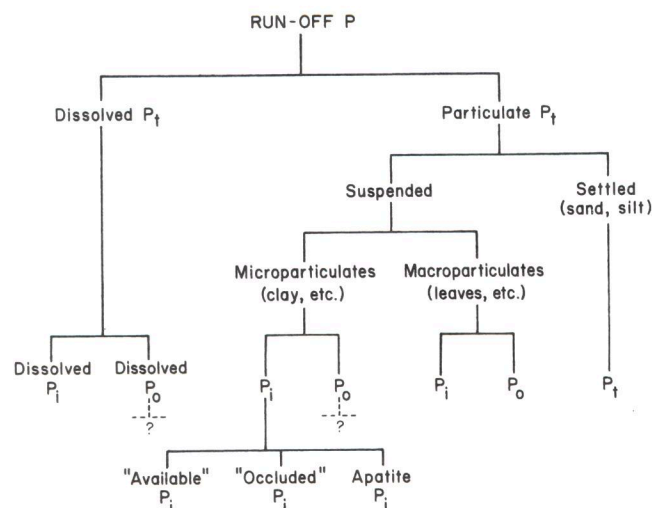Total particulate P (P_t) from runoff was partitioned

Table 1—Dissolved inorganic P (P_i) and total dissolved P (P_t) in urban runoff.

Month, 1971–1972	Storm sewer†	Time elapsed since nearest runoff event	No. of storms	No. of samples	Flow rate range	Dissolved P_t Range	Mean‡	Dissolved P_i mean‡	%§
		days			liters/sec	—— mg P/liter ——		mg P/liter	
Oct.	M	5	1	10	14–64	0.28–2.57	1.83	1.71	93
Nov.	M	2	1	18	10–326	0.25–1.49	0.59	0.55	93
Mar.	M	<1	2	5	1–7	0.18–0.26	0.21	0.19	90
Mar.	N	<1	1	4	11–41	0.12–0.16	0.14	0.11	79
Apr.	M	1	3	20	2–187	0.19–0.39	0.23	0.20	87
Apr.	N	1	3	15	31–454	0.11–0.26	0.16	0.15	94
May	M	<1–12	4	30	1–70	0.13–2.24	0.44	0.36	82
May	N	<1–12	4	49	1–302	0.06–2.29	0.44	0.37	84
July	N	2	1	7	10–402	0.15–0.42	0.24	0.20	83
Aug.	M	3	1	4	73–143	0.10–0.13	0.11	0.10	91
Sept.	M	1–3	5	18	1–975	0.01–0.45	0.22	0.19	86
Oct.	M	<1–4	5	40	1–357	0.04–3.98	1.08	0.99	92
Nov.	M	<1	2	6	5–21	0.99–3.12	2.19	2.11	96

† M = Manitou Way, N = Nakoma storm sewers.
‡ Flow-weighted mean.
§ % of total dissolved P (P_t).

simply into organic and inorganic P. The relevant data for runoff from Manitou Way and Nakoma storm sewers are presented in Tables 2 and 3, respectively. Samples from Manitou Way were taken in the fall and the spring and from Nakoma in the spring alone. In most instances, the samples represent several different phases of a given event. The ranges in concentration shown are for the actual levels of particulate P_t as measured, and the mean values for dissolved P_i,

particulate P_i, and particulate P_t are flow-weighted means.

For Manitou Way, the means for particulate P_t ranged from 0.14 to 1.79 mg P/liter, while individual samples ran from 0.1 to 2.63 mg P/liter (Table 2). The higher mean particulate P_t and dissolved P_i values were associated with leaf fall in the fall, elm fruit fall in the spring, and also with the lapse of the more extended periods between runoff events. The positive relationship

Table 2—Dissolved inorganic P (P_i), particulate inorganic P (P_i), and total particulate P (P_t) in urban runoff from Manitou Way storm sewer.

Date	Time elapsed since nearest runoff event	No. of samples	Flow rate range	Particulate P_t Range	Mean†	Particulate P_i mean†	%‡	Dissolved P_i mean†
	days		liter/sec	—— mg P/liter ——		mg P/liter		mg P/liter
1971								
27 oct.	5	10	14–64	0.44–1.13	0.66	0.19	30	1.71
1 Nov.	2	11	10–326	0.1 –0.31	0.14	0.06	40	0.49
1972								
30 Mar.	<1	3	1–7	0.11–0.32	0.25	0.17	68	0.18
14 Apr.	3	3	7–28	0.37–0.80	0.64	0.49	76	0.19
21 Apr.	1	13	2–187	0.13–0.57	0.38	0.23	61	0.20
28 Apr.	5	2	6	0.14–0.15	0.15	0.09	63	0.32
2 May	<1	3	3–13	0.14–0.15	0.14	0.04	30	0.20
13 May	6	2	59–70	0.41–1.05	0.70	0.26	37	0.19
14 May	<1	10	24–72	0.16–0.96	0.37	0.14	38	0.16
29 May	12	6	1–29	0.74–2.63	1.79	0.16	9	1.40

† Flow-weighted mean.
‡ % of total particulate P (P_t).

Table 3—Dissolved inorganic P (P_i), particulate inorganic P (P_i), and total particulate P (P_t) in urban runoff from Nakoma storm sewer.

Date, 1972	Time elapsed since nearest runoff event	No. of samples	Flow rate range	Particulate P_t Range	Mean†	Particulate P_i mean†	%‡	Dissolved P_i mean†
	days		liter/sec	—— mg P/liter ——		mg P/liter		mg P/liter
30 Mar.	<1	4	11–41	0.18–0.52	0.30	0.12	39	0.11
21 Apr.	1	10	66–454	0.16–0.48	0.31	0.20	66	0.15
28 Apr.	5	2	31–33	0.17–0.30	0.23	0.11	49	0.20
2 May	<1	4	66–97	0.11–0.17	0.14	0.05	35	0.07
13 May	6	3	2–3	0.10–0.35	0.19	0.13	69	0.13
14 May	<1	7	88–179	0.10–0.36	0.20	0.08	39	0.13
29 May	12	20	1–302	0.14–4.09	2.37	0.59	25	0.59
30 May	<1	6	1–51	0.25–0.42	0.33	0.10	31	0.18

† Flow-weighted mean.
‡ % of total particulate P (P_t).

between the length of antecedent dry periods and the levels of P and other pollutants has been observed in atmospheric washout (16), and urban runoff (20, 31).

Values for mean particulate P_i ranged from 0.04 to 0.49 mg P/liter. For the runoff in March and April, particulate P_i as a percentage of particulate P ranged from 61% (21 Apr. 1972) to 76% (14 Apr. 1972), whereas for the remaining samples from May, October, and November this percentage goes from 9% (29 May 1972) to 40% (1 Nov. 1971). The discernible trend is that, whereas at low levels of particulate P_t, i.e., ≤0.40 mg P/liter, the proportion represented by particulate P_i could be high or low, at higher levels of particulate P_t this proportion is usually small. Thus, while correlations between particulate P_t and particulate P_i were not significant, particulate P_t and particulate P_o were correlated significantly at the 99.9% level of probability.

The data for Nakoma sewer are presented in Table 3. The individual sample concentrations of particulate P_t ran from 0.10 to 4.09 mg P/liter and the means from 0.14 to 2.37 mg P/liter. Values for particulate P_i ranged from 0.05 to 0.59 mg P/liter. These mean P levels are quite similar to those obtained for Manitou Way (Table 2). The proportion of particulate P_t constituted by particulate P_i varied substantially, ranging from 25% (29 May 1972) to 69% (14 Apr. to 13 May 1972) (Table 3). High levels of particulate P_t were usually associated with low proportions of particulate P_i, same as for Manitou Way. However, for Nakoma both particulate P_i and P_o were significantly correlated with particulate P_t at the 99.9% level of probability. In addition, the influence of the temporal separation of events was not as marked as for Manitou Way.

The mean dissolved P_i concentrations for Manitou Way and Nakoma runoff ranged from 0.16 to 1.71 mg P/liter and from 0.07 to 0.59 mg P/liter, respectively (Tables 2 and 3). Except for one high value (Manitou Way, 1.40 mg P/liter), for comparable times of the year the dissolved P_i levels for the two sewers were similar. However, for Manitou Way mean dissolved P_i concentrations correlated significantly only with particulate P_t and P_o, and at the 95% level of probability, whereas for Nakoma, the mean dissolved P_i correlated significantly with particulate P_t, P_i, and P_o all at the 99.9% level of probability. Evidently, the effect of the holding pond in the Nakoma system was to allow a greater equilibration and to produce more homogeneity among the various P components than occurs in the Manitou Way System.

Since, for this investigation, the primary interest in runoff P is in its effect on the photic zone, the settling rate of the particulate P_t is a very important characteristic, in addition to its chemical composition. The longer that a particle stays in the photic zone, the greater its potential for supplying P for biological growth therein. The settling characteristics of the particulate P_t in runoff from three storms are given in Table 4. For the storms on 14 July, 19 July, and 14 Aug. 1972, the nearest antecedent storm occurred 2, 2, and 3 days earlier, respectively. The particulate P_t from different hydrograph stages is fractionated according to settling rate. The first flush period of the hydrograph is that portion of the runoff occurring between the start of the

Table 4—Settling rate characteristics of total particulate P (P_t) in urban runoff.

Date, 1972	Storm sewer†	No. of samples	Particulate P_t	Particulate P fraction of settling rate, cm/min		
				<0.1	0.1–1.0	>1.0
			mg P/liter	% of particulate P_t		
Flush period						
14 July	N	1	1.42	49	22	29
19 July	N	1	0.55	46	36	18
High flow (>400 liter/sec)						
14 July	N	2	1.15	38	31	31
19 July	N	2	0.72	35	36	29
14 Aug.	M	6	0.50	41	25	34
Low flow (<75 liter/sec)						
14 July	N	1	0.50	74	26	0
19 July	N	1	0.30	80	20	0

† N = Nakoma, M = Manitou Way storm sewers.

event and the peak flow rate or here 400 liter/sec for high-intensity storms. Discharge occurring in this phase often has a substantially greater contaminant concentration than the remainder of the runoff.

The data provided shows that, for all flow periods, a major portion of the particulate P_t was comprised of particles that settled very slowly, i.e., at <0.1 cm/min, and, in particular, in the low-flow period when 74 to 80% fell into this class. In fact, a substantial portion of this class (<0.1 cm/min) actually settled at <0.01 cm/min. Particles settling at <0.1 cm/min are likely to remain in the photic zone for several days allowing interaction with the lake water therein as well as with its biological component. That a high proportion of particulate P_t was associated with the finer particles concurs with findings for street debris (20) as well as for soils (22, 25, 32). The phenomenon evidenced here is identical with that observed in soil erosion studies, where the selectivity of surface runoff for finer particles produces an actual enrichment in the proportion of P in the transported particulate phase (18, 24).

Particles settling at >1 cm/min provided significant proportions (18 to 34%) of the particulate P_t during the initial flush and high-flow periods but contribute nothing to the subsequent low-flow period. These particles would within 5 hours drift through 305 cm (10 feet), i.e., to the lake bottom for most locations in Lake Wingra. Particles of intermediate settling rate (0.1 to 1.0 cm/min) comprised substantial proportions (20 to 36%) of the particulate P_t in all periods of flow and thus may serve as a supplier of P for algal growth under P stress, but to a lesser extent that the finest particles. For all phases of the hydrograph, the relative proportions falling into the different settling categories did not change much with particulate P_t concentration.

The relative impact of the particulate P transported during the different flow periods would be determined by the actual P loading during each phase, as well as the chemical forms of the particulate P at these times. Since it is likely that the major portion of P loading from a runoff event usually occurs during the flush and high-flow periods, the data relating to these phases should be appropriately emphasized.

General Discussion

Phosphorus is a key element targeted for the control of lake eutrophication (12, 13). Projected improvements in the P levels of municipal waste treatment effluents (13) increase the significance of the P contributions from urban stormwater runoff to lakes in the urban watersheds. Thus the characterization of the forms of P in runoff and their pattern of occurrence becomes more important. Such information would allow the optimization of sampling and analytical procedures to obtain reliable and relevant P loading data.

Since dissolved P_i is the only form of P that is directly available to algae (etc.), it is important that a good estimate of this be obtained from any analyses of runoff P. The results presented in Table 1 indicate that dissolved P_i consistently represents the major portion of the dissolved P_t in urban runoff. This allows: i) a simple approximation of dissolved P_i from the determination of either dissolved P_i or total dissolved P; ii) a good approximation of particulate P from the determination of total P and either dissolved P_i or total dissolved P; and iii) increased sample storage options since simple filtration, through a 0.45-μm membrane filter, and acidification are all that would be necessary prior to storage of samples for dissolved P_t analysis. This represents the optimal situation for the analytical disposition of runoff samples.

However, it is not typical of natural waters to show a consistently high proportion of dissolved P_t as dissolved P_i. Lake waters, for example, show markedly varied proportions with time of year (10, 27). The extent to which the observed P distribution is true for runoff from other cities is presently unclear since this information has been lacking in the literature.

The importance of particulate P from storm runoff depends on its chemical composition and its settling characteristics. Data presented in Tables 2 and 3 suggest that mean particulate P_i concentrations in runoff are usually low. They also show a tendency towards a higher proportion of organic than inorganic in the particulate P_t. Further, correlation analyses indicate a more consistent relationship for mean particulate P_o than for mean particulate P_i with respect to the mean dissolved P_i, from storm to storm. But limited data (6) implicate the inorganic phase as the predominant determinant of P_i release from urban runoff particulates to solution, in well-equilibrated systems. This suggests a reversal in emphasis from organic to inorganic particulate P upon transport of particulates from the incompletely equilibrated storm sewer system, to the lake where increased residence time permits greater equilibration. However, estimates of available P based on algal bioassays of unfractionated samples ranged from 8 to 55% of this particulate P_t with a mean of 30% (6). Comparisons of the proportions of particulate P_t that are available with the proportions that are acid-extractable (6) and also with the proportions of P_i in particulate P_t from this investigation (Tables 2 and 3), imply a significant contribution of particulate P_o to the available P, at least in some instances.

Data presented in Table 4 indicate that, for the major loading phases of runoff events, a significant proportion (35 to 50%) of particulate P will commonly remain in suspension in the photic zone for a period of several days. If the maximum availability (55%) cited above is assigned to this fraction of the particulate P_t, then a conservative estimate of the upper limit for potentially available particulate P_t from urban runoff on a routine basis is ~25%. Thus the potential contribution of urban runoff P to eutrophication could be based reasonably on two analyses: dissolved P_i (or dissolved P_t) and particulate P_t, potentially available P being approximated by: dissolved P_t plus 0.25 × particulate P_t. The extent to which the observed concentrations of P in the dissolved and particulate phases of urban runoff exceed the threshold value of 0.01 mg P/liter (21) for algal nuisance conditions indicates the eutrophying potential of this discharge. However, the actual contribution of runoff would depend also on the P loading relative to the P already in the receiving waters and the adequacy of other factors such as other nutrients, and temperature which may limit biological growth.

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The Effects of Fluometuron on a Salt Marsh Ecosystem[1]

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ABSTRACT

A salt march on Sapelo Island, Georgia, dominated by a monospecific stand of spartina (*Spartina alterniflora* Loisel) was treated with fluometuron [1,1-dimethyl-3-(α,α,α-trifluoro-*m*-tolyl)urea]. Treatments were: spraying once each year with 90,000 ppm; spraying 30 times (twice each day for 5 consecutive days in 3 consecutive months) with 1,000, 100, 10, 1, or 0 ppm; or flooding 30 times (frequency as described above) with 100 or 0 ppm. One-half of each plot was re-treated in the same manner the second year while the other half was left untreated. Effects on spartina, periwinkle snails (*Littorina irrorata* Say), and horse mussels (*Gukensia demissus* Dillwyn) were measured 4 mo after the first treatment. Only spraying once with 90,000 ppm fluometuron or 30 times with 1,000 ppm significantly reduced fresh weight, dry weight, or number of shoots of spartina and re-treatment the second year at the same rates did not increase the effect. The spartina on the plots treated the first year but not retreated the second year recovered completely. One year after the last of 30 sprayings with 1,000 ppm or 1 spraying with 90,000 ppm, there were significant levels of fluometuron residue in the spartina harvested from these plots.

Flooding 30 times with 100 ppm of fluometuron did not significantly decrease the total fresh or dry weight of spartina, but did cause visible injury symptoms and did decrease the number of shoots. Flooding 30 times with 100 ppm was nearly as toxic as spraying 30 times with 1,000 ppm. Neither flooding nor spraying adversely affected the number or weight of snails. The snails were not confined to the plots but fluometuron residues in them reflected the treatment rates so migration into or out of plots must have been minimal. Flooding with 100 ppm fluometuron did not adversely affect the mussels.

Additional Index Words: pesticides, spartina, snails, mussels.

Salt marshes occur all along the eastern coast of the United States behind the barrier islands and on the islands themselves. The importance of these marshes is now widely recognized (2, 3). However, many things threaten the productivity and, in some cases, the continued existence of these marshes. Among these are agricultural chemicals either applied directly to the marshes for insect or vegetational control or brought into the marshes by rivers carrying runoff water from treated agricultural land. The objective of this study was to determine the effects of the herbicide fluometuron on the salt marsh ecosystem. The site of the study was the medium salt marsh at Sapelo Island, Georgia. This particular marsh type has been fully described by Johnson et al. (4).

This medium salt marsh ecosystem is dominated by *Spartina alterniflora* Loisel, hereafter referred to as spartina. The primary producers in this ecosystem are spartina and algae (primarily diatoms). Spartina is a C-4 plant and one of the most productive species known. Teal (7) gives the yearly net productivity of spartina as